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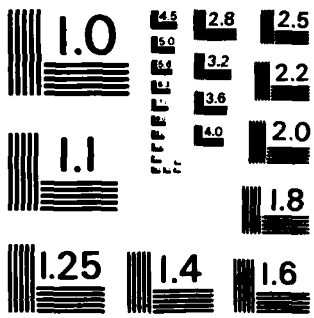

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October 1985

Empirical Equations for Drift Velocities in Silicon

by Alford L. Ward

U.S. Army Electronics Research
and Development Command
Harry Diamond Laboratories
Adelphi, MD 20783-1197

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1. REPORT NUMBER HDL-TM-85-9	2. GOVT ACCESSION NO. A162 743	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) Empirical Equations for Drift Velocities in Silicon		5. TYPE OF REPORT & PERIOD COVERED Technical Memorandum
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) Alford L. Ward		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS Harry Diamond Laboratories, 2800 Powder Mill Road, Adelphi, MD 20783-1197		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS Program element: 63749A DA project: 1L263749D462
11. CONTROLLING OFFICE NAME AND ADDRESS U.S. Army Electronics Research & Development Command, Adelphi, MD 20783-1145		12. REPORT DATE October 1985
		13. NUMBER OF PAGES 15
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report) UNCLASSIFIED
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

AMS code: 623749.462.0012
HDL project: E02525
PRON: 1F-5-C0004-56-A9

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Drift velocity, Electric field, Silicon, Temperature, Doping level

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Empirical equations for the drift velocities of electrons and holes in silicon are given as a function of electric field, temperature, and doping density. A single equation, which is valid above room temperature, results from the inverse dependence of the saturation velocity upon the square root of the temperature.

Foreword

Hardening against the electromagnetic pulse and high power microwave radiation is an important part of Harry Diamond Laboratories' mission, and semiconductor modeling is an important component of the hardening effort. Vital to semiconductor modeling of burnout are the transport properties of semiconductors at high fields and high temperatures. At present, there is no single expression valid for this hot electron regime. The results of this study will be used in the thermal modification of the DIODE2D program, now underway.

A recent report of the National Research Council, *Evaluation of Methodologies for Estimating Vulnerability to Electromagnetic Pulse Effects*,* recommended that "There should be a better understanding of the mechanisms of component failure...."

The theoretical work included in this report provides physical insight into the damage mechanisms and should lead to nondestructive means of characterizing specific devices.

**Defense Nuclear Agency, DNA-TR-84-78, National Academy Press (1984), 4.*

Contents

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1. Introduction

Simple empirical equations for the drift velocities of electrons and holes as a function of electric fields, temperature, and doping levels are needed for device simulation. A review of charge transport properties of silicon, including phenomenological expressions, was given by Jacoboni et al.[1] However, none of their expressions included all three of the variables of interest. Schwarz and Russek[2] presented semi-empirical equations for electrons in silicon, but their expressions are not simple to use. The well-known empirical equation of Scharfetter and Gummel[3] is for room-temperature only.

2. Derivation of Equation

The equation of Scharfetter and Gummel[3] for the drift velocity, v_d, as a function of field, E, and doping level, N, is

$$v_d = \mu_0 E/(\{1 + N/[(N/S) + N_R] + (E/A)^2/[(E/A) + F] + (E/B)^2\})^{1/2} , \tag{1}$$

where μ_0 is the low-field mobility and all other symbols are fitting parameters. The temperature dependence of μ_0 is generally given as

$$\mu_0 = CT^{-\gamma} , \tag{2}$$

where T is temperature and C and γ are constants. The power dependence varies according to the investigator, but is usually around 2.5 for both holes and electrons.

The temperature variation of the saturation velocity, v_s, for electrons was measured by Duh and Moll.[4] Their data are plotted on a log-log scale in figure 1. It is seen that there is a close fit to a power law, i.e.,

$$v_s = K/T^{1/2} , \tag{3}$$

in the range above room temperature.

An empirical expression for v_s is given by Jacoboni et al[1] as

$$v_s = v^*/[1 + G \exp(T/\Theta)] , \tag{4}$$

where $v^* = 2.4 \times 10^7$ cm/s, G = 0.8, and Θ = 600 K. This expression is also plotted in figure 1.

The saturation velocity from (1) is found to be

$$v_s = \mu_0 B . \tag{5}$$

By equating (3) and (5) we obtain, from (2),

$$B = DT^{\gamma - 1/2} , \tag{6}$$

where D = K/C. Finally, using (2) and (6) in (1) we obtain our desired expression,

$$v_d = (CT^{-\gamma}E)/[1 + N/[(N/S)N_R] + [(E/A)^2]/[(E/A) + F] + (E/DT^{-1/2})^2]^{1/2} \tag{7}$$

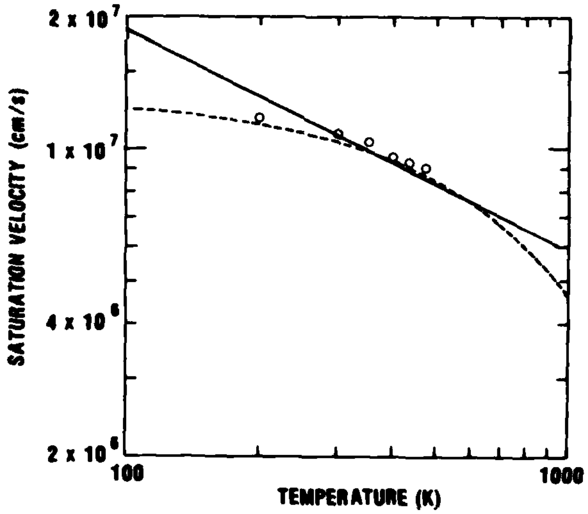

Figure 1. Saturation velocity as function of T. Points are measured data of Duh and Moll.[4] Dashed line is from equation (4) and solid line from equation (3).

3. Results

Plots of v_d from equation (7) for electrons in silicon are given in figure 2 for N = 0 at 300, 400, 500,

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[1] *C. Jacoboni, C. Canali, G. Ottaviani, and A. Alberigi Quaranta, A Review of Some Charge Transport Properties of Silicon, Solid-State Electron., 20 (1977), 77-89.*

[2] *S. A. Schwarz and S. E. Russek, Semi-Empirical Equations for Electron Velocity in Silicon: Part I—Bulk, IEEE Trans. Electron. Devices, ED-30 (1983), 1629-1633.*

[3] *D. L. Scharfetter and H. K. Gummel, Large-Signal Analysis of a Silicon Read Diode Oscillator, IEEE Trans. Electron. Devices, ED-16 (1969), 64-77.*

[4] *C. Y. Duh and J. L. Moll, Temperature Dependence of Hot Electron Drift Velocity at High Electric Field, Solid-State Electron., 11 (1968), 917-932.*

and 600 K. The parameters used are listed in table 1. Also plotted in figure 2 are 600-K curves for doping levels of 1×10^{17}, 1×10^{18}, and 1×10^{19} cm^{-3}. All curves are seen to be smooth. Room-temperature plots of v_d as a function of E for various doping levels may be found in Jacoboni et al.[1] Plots of the temperature dependence of v_d at fixed fields show a gradual decrease in the exponent of T from γ at low fields to 1/2 at high fields. Plots have been made of hole drift velocities from equation (7) and from the parameters of table 1, and they also show smooth variations.

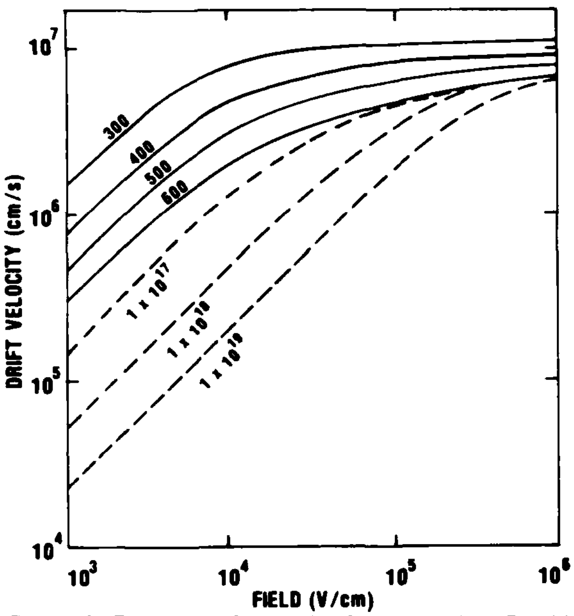

Figure 2. Electron drift velocity from equation (7) with parameters of table 1. Solid curves are for N = 0 and constant temperatures (K) as labeled. Dashed curves are for T = 600 K and doping densities (cm^{-3}) as labeled.

Table 1. Parameters used in equation (7) for calculating drift velocities

Parameter	Electrons	Holes	Units
A	3.5×10^3	6.1×10^3	V/cm
C	1.43×10^9	1.35×10^8	$cm^2K^{\gamma}V^{-1}s^{-1}$
D	1.29×10^{-1}	1.37	$cmK^{1/2-\gamma}s^{-1}$
F	8.8	1.6	—
N_R	3×10^{16}	4×10^{16}	cm^{-3}
S	350	81	—
γ	2.42	2.2	—

[1] C. Jacoboni, C. Canali, G. Ottaviani, and A. Alberigi Quaranta, *A Review of Some Charge Transport Properties of Silicon*, Solid-State Electron., 20 (1977), 77-89.

Cook and Frey[5] have measured the high-field electron drift velocity in silicon-on-sapphire (SOS) films doped to $N = 2 \times 10^{17}$ cm^{-3}. Their data are plotted in figure 3. Also plotted in this figure are calculations based on equation (7) and the parameters of table 1. The low-field mobility was reduced by 50 percent in a second calculation, also plotted in figure 3. To show the flexibility of (7), the parameter F was set at ∞ (i.e., the third term of the denominator was set to zero), and the lower mobility calculation was repeated. The fit to the experimental data is quite good. Schwarz and Russek[2] predict the steeper rise in the velocity-field profile in doped silicon. When further data are available, the parameters A and/or F could perhaps be made dependent upon the doping level.

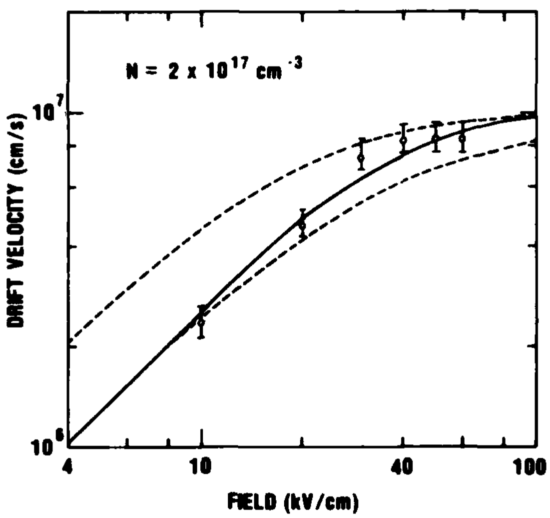

Figure 3. Electron drift velocity as function of field for $N = 2 \times 10^{-17}$ cm^{-3} *and room temperature.* Experimental points with error bars are from Cook and Frey.[5] Upper dashed curve is from equation (7) with table 1 parameters. Lower dashed curve is calculated with lower mobility, but same saturation velocity. Solid curve shows latter mobility with third term of denominator of equation (7) omitted.

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(1) C. Jacoboni, C. Canali, G. Ottaviani, and A. Alberigi Quaranta, *A Review of Some Charge Transport Properties of Silicon*, Solid-State Electron., 20 (1977), 77-89.

[2] S. A. Schwarz and S. E. Russek, *Semi-Empirical Equations for Electron Velocity in Silicon: Part 1—Bulk*, IEEE Trans. Electron. Devices, ED-30 (1983), 1629-1633.

[5] R. K. Cook and J. Frey, *High-Field Electron Transport in Silicon-on-Sapphire Layers*, J. Appl. Phys., 51 (1980), 2556-2558.

(2) S. A. Schwarz and S. E. Russek, *Semi-Empirical Equations for Electron Velocity in Silicon: Part I—Bulk*, IEEE Trans. Electron. Devices, **ED-30** (1983), 1629-1633.

(3) D. L. Scharfetter and H. K. Gummel, *Large-Signal Analysis of a Silicon Read Diode Oscillator*, IEEE Trans. Electron. Devices, **ED-16** (1969), 64-77.

(4) C. Y. Duh and J. L. Moll, *Temperature Dependence of Hot Electron Drift Velocity at High Electric Field*, Solid-State Electron., **11** (1968), 917-932.

(5) R. K. Cook and J. Frey, *High-Field Electron Transport in Silicon-on-Sapphire Layers*, J. Appl. Phys., **51** (1980), 2556-2558.

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